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Braking of an Aircraft Tire on Grooved and Porous Asphaltic Concrete

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Final Report

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16. Abstract

Runway grooving is an effective surface treatment that reduces the danger of hydroplaning to an aircraft landing on a water-covered runway. Grooves are usually cut by diamond-tipped rotatory blades; square grooves of 1/4-inch size are widely used. Other surface treatments include grooving by a reflex-percussive cutting process, gooving while the concrete is in plastic state, and the porous friction overlays. Grooving in plastic state is limited to portland cement concrete runways only while the other treatments can be applied to both the portland cement concrete and the asphaltic concrete surfaces. The effectiveness of some of these treatments has not been evaluated on asphaltic concrete surfaces prior to the initiation of this study.

This report describes an experimental program that investigated the braking and hydroplaning performance of an aircraft tire on asphaltic concrete surfaces having various treatments. The tests were conducted on a dynamic track in the speed range of 70 to 150 knots, and under other operating conditions whose magnitudes represented values widely used by airlines or aircraft. The results show that the type of surface treatment has a significant influence on the braking performance of an aircraft tire on "puddled" runways, grooves at closure spacings provide higher friction levels. When the runways are "wet" or "flooded" the braking capability on all surfaces is either very high or very low, respectively. The braking performance on the reflex-percussive grooves, the porous friction overlay, and the saw-cut grooves spaced at 3 inches is comparable.

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Runway Surface Treatment, Hydroplaning, Asphaltic Concrete, Braking Performance, Reflex-Percussive Grooves, Porous Friction Overlay, Wet Runways, Reflex-Saw-Cut Grooves,

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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

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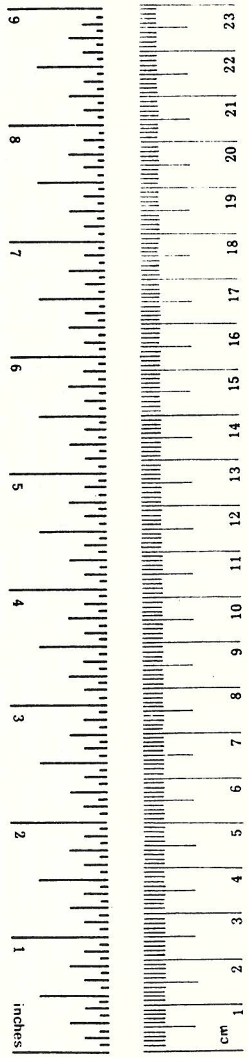
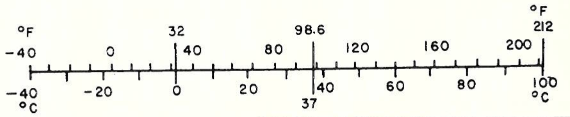
*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



PREFACE

The work described in this report was undertaken and accomplished by the personnel of the Federal Aviation Administration Technical Center. The request of work for this research, development, and engineering effort was made by the Office of Airport Standards in the Federal Aviation Administration. Mr. Herman D'Aulerio of the Aircraft Safety and Airport Technology Division provided program direction. The Naval Air Engineering Center at Lakehurst, New Jersey, provided the test facility, test facility operation, and data acquisition systems. The test program was conducted under the direction of Mr. Hector Daiutolo of the Federal Aviation Administration Technical Center.

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EXECUTIVE SUMMARY

Since 1976, the FAA Technical Center has been engaged in an experimental program to determine low-cost surface treatment for runways. Some of the treatments are: saw-cut grooves, reflex-percussive grooves, and porous friction overlay. The FAA has recommended 1/4-inch square conventional saw-cut grooves, spaced at 1 1/4 inches, for installation on runways where the potential of aircraft hydroplaning exists. However, a larger number of runways remain nongrooved. The major reasons are the high cost of groove installation, and availability of only limited evidence as to the effectiveness of the grooved surfaces at the touchdown speeds of modern aircraft.

The FAA experimental program was accomplished in two phases. The first phase was completed in 1980, and consisted of testing on portland cement concrete surfaces. The program was conducted on a dynamic test track at the Naval Air Engineering Center, Lakehurst, N.J. The concrete test bed consisted of several sections of conventional saw-cut grooves at various spacings, a section of newly-developed reflex-percussive grooves, and a few sections with no grooves. The tests were conducted with a Boeing-727 tire in the speed range of 70 to 150 knots, and under other operating conditions whose magnitudes represented values widely used by airlines and aircraft. The results showed that the conventional saw-cut grooves spaced at 3 inches or less will provide "acceptable braking performance" to an aircraft tire on water covered runways, and the installation cost of the 3-inch spaced grooves could be 25 percent less than that of the installation cost of grooves spaced at 1 1/4 inches. The results further showed that the reflex-percussive grooves, an alternative to conventional saw-cut grooves, provided sufficient braking to allow an aircraft to stop without experiencing hydroplaning.

The second phase of the experimental program was conducted on the asphaltic concrete bed and is the subject matter of this report. The investigation included the conventional saw-cut grooves at various spacings, the reflex-percussive grooves, and the porous friction overlay. The results show that the reflex-percussive grooves, the porous friction overlay, and the conventional saw-cut grooves spaced at 3 inches perform comparably. The closely-spaced conventional saw-cut grooves are desirable where the seasonal and topographical conditions consistently produce "puddled" water conditions on the runways. The "puddled" conditions represent average water depth of approximately 0.10 inch.

INTRODUCTION

An aircraft is brought to a complete stop on the runway by the combined forces of aerodynamic drag, reverse engine thrust, and wheel braking. The effectiveness of wheel braking varies with the wetness of the runway. The total distance required for bringing a landing aircraft to a complete stop can fluctuate widely, depending upon the friction level available at the tire-runway interface. When this interface is dry, the friction level is high and the aircraft can be brought to a stop quickly; however, the presence of water at the interface reduces the available friction level significantly, and hazardous conditions of overrun and hydroplaning exist.

Runway grooving has been recognized as an effective means of minimizing the danger of hydroplaning. The grooves provide escape paths for water in the tire-runway contact area during the passage of the tire over the runway. In addition, the isolated puddles that are likely to be formed on nongrooved surfaces because of uneven surface profile are generally reduced in size or eliminated when the surface is grooved. This advantage is particularly significant in the regions where large ambient-temperature variations may cause low magnitude undulations in the runway surface.

Runway grooves are usually cut by diamond-tipped rotary blades. Various groove configurations have been used on the runways; however, square grooves of 1/4-inch size and at groove spacing between 1 inch and 2 1/2 inches have been widely used. Recently, a few runways have been grooved at a spacing of 3 inches. Other methods of surface treatment that have been reported as being effective in minimizing hydroplaning on runway surfaces include porous friction overlays, grooving by high-speed water jet, grooving while the concrete is in plastic state, grooving by vibration kerfing, and grooving by reflex-percussive cutting process. However, only the porous friction overlays, plastic state grooving, and the reflex-percussive cutting process have been found to be viable cost competitive methods. Porous friction overlays have been used on asphaltic concrete runways, and plastic state grooves on portland cement concrete runways.

The grooves provided by the reflex-percussive cutting process are still in an experimental stage, however, their cost-effectiveness has been demonstrated by the Federal Aviation Administration (FAA) in the portland cement concrete (PCC) surface by full-scale tire tests under controlled dynamic conditions. Since 80 percent of all the runways in the United States are of asphaltic concrete construction, it is important to evaluate the effectiveness of these experimental grooves cut in asphaltic concrete. It is also necessary to determine the relative braking performance of an aircraft tire, under controlled dynamic conditions, on saw-cut grooves cut in the asphaltic concrete surface, particularly in the absence of any such investigation in the past. Full-scale aircraft tests have been conducted on asphaltic concrete surfaces by the National Aeronautics and Space Administration (NASA); however, groove spacing was not a variable in that study. A direct comparison of the reflex-percussive grooves, saw-cut grooves, and porous friction overlay in asphaltic concrete is the primary objective of this report. It is expected that such a comparison will provide information about a cost-effective surface treatment for asphaltic concrete runways.

OBJECTIVE

The objective of the research and testing described in this report is to investigate the braking and hydroplaning behavior of an aircraft tire on asphaltic concrete surface.

This investigation was accomplished under various degrees of wetness and having the following surface treatments:

1. Saw-cut grooves at various spacings.
2. Reflex-percussive grooves.
3. Porous friction overlay.

BACKGROUND

AIRCRAFT TIRE HYDROPLANING.

The magnitude of the coefficient of friction is influenced by many parameters. The important ones are: speed of operation, water depth, runway surface texture and drainage capacity, condition of tire tread, and the characteristics of the braking system. In general, an aircraft experiences an increase in available friction on a water covered runway as it is decelerated by the action of brakes. A high level of available friction at the start of the deceleration process will provide better braking and directional control; a low level of available friction at the start of the deceleration process will adversely affect the braking and directional control of the aircraft. A complete loss of braking and directional control results when the available friction at the tire-runway interface approaches zero, and even a moderate wind can push the aircraft off the runway. Such a condition exists when the aircraft encounters the state of hydroplaning.

Hydroplaning is a peculiar tire-to-runway condition where the aircraft tire is physically separated from the runway surface by a layer of water that supports the aircraft weight by developing hydrodynamic and viscous pressures within the water layer. Hydrodynamic and viscous pressures are associated with fluid density and fluid viscosity, respectively. Thus, when runways are flooded with water, fluid density effects cause predominantly dynamic hydroplaning, whereas the fluid viscosity effects which cause viscous hydroplaning are predominant when smooth runways are covered with only a thin film of water. In all cases of water covered runways, however, both effects are present to some degree.

In dynamic hydroplaning, the buildup of hydrodynamic pressures in the tire-runway interface causes inward buckling of the tire surface. The space so created between the tire and the runway is filled with water. A relief in fluid pressures is necessary to regain contact between the aircraft tire and the runway surface for developing higher friction forces for effective braking action and directional control of the aircraft. Partial relief in the hydrodynamic pressures can be obtained by cutting circumferential grooves on the aircraft tire and transverse grooves in the runway surface; grooves of various shapes and sizes can be designed for optimum braking performance. Transverse runway grooves provide longer lasting solution to alleviating hydroplaning than the circumferential grooves on the aircraft tire.

In viscous hydroplaning, a thin film of water separates the tread rubber from the aggregate and binder of the runway surface. The deformation of the tire surface within the tire-runway interface is not as large as in dynamic hydroplaning. For an intimate contact to occur between the tire tread rubber and aggregate material, fine-scale asperities (or microtexture) in the aggregate material are desirable. These asperities can break through the thin water film and relieve the viscous pressures.

RUNWAY GROOVING.

Grooves are small channels of geometrical cross-section. They are cut into the runway surfaces usually by means of diamond-tipped rotory blades. The grooves are cut transversally, i.e., along the width of the runways. A square cross-section is the most widely used shape for the grooves; however, other promising designs have been investigated by researchers (reference 1). Grooves were first introduced by British researchers in 1956 (reference 2).

Pavement grooves have been extensively studied by NASA (reference 3) and the FAA (reference 4). The basic objective of NASA investigation had been to determine the groove configuration that provided the best cornering and braking performance under wet operating conditions. Investigating various groove widths and depths and three groove spacings (1 inch, 1 1/2 inches, and 2 inches), NASA concluded that all groove configurations provided improved cornering and braking performances relative to nongrooved surfaces; however, the 1/4-inch square grooves spaced 1 inch apart provided the greatest increase in available friction (reference 3). Based on these and further tests by NASA (reference 5), the FAA has recommended (reference 6) a standard groove configuration of 1/4-inch depth x 1/4-inch width x 1 1/4-inches spacing and has encouraged airport operators, managers, and owners to groove runways where the possibility of hydroplaning exists. However, many runways remain nongrooved. The major deterrents to the use of runway grooves are the high cost of grooving by the conventional saw-cutting method and the availability of only limited evidence as to the effectiveness of grooved surfaces at the touchdown speeds of jet aircraft.

In its efforts to find a cost-effective groove configuration for the runways, the FAA completed a test program on PCC in 1981 (reference 4). The study concluded that the conventional saw-cut grooves spaced at 3 inches or less will provide acceptable braking performance to an aircraft on water covered runways, and that the cost of installation of grooves at 3-inch spacing is up to 25 percent less than that of the grooves spaced at 1 1/4 inches (reference 7). The study also investigated alternative grooving techniques, including a reflex-percussive cutting process.

The reflex-percussive method of controlled concrete-removal was recognized by the Concrete Society of Great Britain in 1972. This method was first developed to obtain a rough finish on the pavement. When the cutting head strikes the surface of the concrete it causes the material directly under the area of impact to deflect downward, thus creating a momentary and localized compression. The compressive strain is mainly elastic, and it is almost immediately given up in generating a rebound that causes the concrete to attempt to pass through its relaxed state into one of tension nearly equal to the initial compression. However, being very weak in tension, the concrete fractures and elastic energy is given up as kinetic energy of the flying fragments. The great advantage of this method of cutting is its ability of not loosening the aggregate particles within the matrix or not creating microfractures in the surrounding concrete. Although still experimental, this method has been very successful in cutting the grooves in PCC; however, the grooves in the asphaltic concrete surfaces have been less successful. The 1981 FAA study (reference 4) compared the braking performance of an aircraft tire on the reflex-percussive grooves in PCC with that of the conventional saw-cut grooves. The general conclusion was that the braking performance on reflex-percussive grooves (spaced at 4 1/2 inches) was equivalent to that on conventional saw-cut grooves spaced at 2 inches, and that the installation cost of the reflex-percussive grooves could be as low as half the cost of conventional saw-cut grooves spaced at 1 1/4 inches. Thus, the FAA study (reference 4) provides information about a cost-effective groove configuration in two ways: (1) by increasing grooves spacing of the conventional saw-cut grooves or (2) by installing reflex-percussive grooves. However, this information requires verification on asphaltic concrete surfaces. In addition, other promising methods of groove installation or surface treatments should be continuously investigated.

GROOVING, DRAINAGE, AND HYDROPLANING.

The improved braking performance on a grooved runway is the result of a dual process of water removal from the tire-runway interface. First, the grooves influence the surface water drainage (runoff) by providing channels through which water can flow freely. How an increase or a decrease in the groove spacing influences the drainage is a subject under controversy. However, preliminary results from an analytical study (reference 8) show that a slight decrease in water depth occurs with decreasing groove spacing for the saw-cut grooves of square cross section. The magnitude of water-depth reduction was approximately 10 percent in going from 3-inch groove spacing to 1 1/4-inch groove spacing. These results were valid for a rainfall rate of up to 6-inches per hour, surface texture depth of up to 0.03 inch, and at locations of up to 100 feet from the runway centerline. The free flow of water is determined by groove spacing, surface texture, and runway slope. The smaller groove spacing provides better free flow in terms of smaller water depth; however, increasing the groove spacing does not increase the water depth in the same proportion as the groove spacing ratio.

Second, the grooves provide forced water escape from the tire-runway interface when the aircraft travels on a water covered runway. Since the maximum amount of water that can be removed from the runway in a given time is limited, both the free flow and the forced escape of water are important.

Relationship between grooving and forced water escape is influenced by the amount of water on the runway and the speed of aircraft. As mentioned earlier, runway grooves can provide relief in the hydrodynamic pressure developed within the tire-runway interface. Since fluid pressures are predominantly hydrodynamic when runways are flooded, grooves will be very effective on these runways. On the other hand, when the runways are covered with only a thin film of water, where predominantly viscous pressures are developed within the tire-runway interface, grooves may not be as effective as the sharp-textured aggregates in the runway surface; the pressure relief is accomplished by sharp aggregates breaking the thin water film between the tire and the runway. In the intermediate condition, between thin film and flooding, both grooves and sharp-microtexture aggregates are desirable. The speed of the aircraft determines the amount of water that can be expelled from the tire-runway interface. Because of the inertia of water, the escape is retarded as the speed is increased. Thus, inherently, a lesser amount of water will be expelled (from the tire-runway interface) at higher aircraft speeds.

TESTING APPROACH

The measurement of hydroplaning of an aircraft tire is a complex problem that involves simulating the braking operation of an aircraft tire on a wet or flooded runway. The FAA accomplishes this task at the Naval Air Engineering Center, Lakehurst, New Jersey. The details of the test facility, test parameters, and test procedure will be discussed in the following sections. This section describes the measurement parameters and how they relate to braking performance.

The coefficient of friction, as computed by dividing the tangential forces developed at the tire-runway interface by the vertical load on the tire, determines the relative performances of the surfaces tested. As the coefficient of friction decreases, so does the braking capability. In the limiting case, when the coefficient approaches zero, hydroplaning is said to occur. However, the friction coefficient can not be equal to zero because of the presence of small viscous and hydrodynamic drag forces at the tire-runway interface. Thus, a direct measurement of the speed at which hydroplaning occurs is not possible. Various indirect methods have been used in the past (reference 9) to identify the onset of hydroplaning. In the present study, incipient hydroplaning is indicated when the measured coefficient of friction is 0.05 or lower. In comparison, the average coefficient of friction between the aircraft tire and the dry runway is approximately 0.7.

Frictional forces are developed as a result of relative motion between two surfaces; the tire-runway combination is no exception. It is well documented that as the tire slips in the contact area, a progressively increasing friction coefficient is developed. Tire slip is an indication of the departure of the angular velocity of the braked tire from the free-rolling velocity. Thus, a locked tire represents 100 percent slip while a free-rolling tire is under no slip. A slip of between 10 and 20 percent has been identified as the value beyond which the coefficient of friction starts to decrease. This behavior is more pronounced when the tire-runway interface is dry. For wet interfaces, the coefficient of friction remains level over a wide range of slip value; this makes it more difficult to determine the maximum value of friction coefficient under wet interface conditions.

There are two methods by which a meaningful comparison of various surface treatments can be accomplished: (1) measurement of coefficient of friction when the tire is locked and slides over the test surfaces, or (2) measurement of maximum available value of the coefficient of friction on each test surface. The present study employs the second method, even though it requires many more tests than the first method. The disadvantage with the first method is an accelerated treadwear of the tire that will require frequent tire changes; danger of tire blow-out is also present in the first method. The advantage with the second method is that it represents a realistic simulation of the braking process of an aircraft.

To obtain the maximum coefficient of friction available for a given set of speed, water depth, and surface type (treatment), multiple tests were performed. The first test was conducted at a relatively low brake pressure to assure that wheel lock would not occur. Subsequent tests were conducted at gradually increasing brake pressures. In each test, the magnitudes of the coefficient of friction and tire slip were monitored; both the coefficient and the slip increased with increasing brake pressure. A drop in the coefficient or sudden increase in the slip indicated that the maximum value of the coefficient of friction had been obtained in the previous test. This procedure was followed throughout the test program. To eliminate undesired sliding of the test tire, automatic brake release was initiated just beyond the test surface in question.

EXPERIMENTAL PROGRAM

TEST FACILITY AND EQUIPMENT.

The experimental program was conducted at track No. 3 of the Naval Air Engineering Center, Lakehurst, New Jersey. The track is 1 1/4 miles long and has guide rails spaced 52 1/4 inches apart running parallel to the track centerline. Reinforced concrete strips extending beyond the guide rails to a width of 28 feet also run parallel to the track. The concrete strips are 8 inches thick. The last 300 feet of the track was used for installing the test bed. The test bed was installed on the PCC surface existing on the track. The test bed was 2 1/2 inches thick and 30 inches wide and was made of asphaltic concrete. An aircraft arresting system is located beyond the test track to recover the test equipment at the completion of a test run.

The major components of the test equipment are: the four-wheeled jet car, the dead-load carriage which supports the dynamometer and wheel assembly, and the measuring system. The jet car (figure 1) is powered with four J48-P-8 aircraft engines developing a total thrust of 24,000 pounds. The jet car is used to propel the dynamometer and wheel assembly and the carriage from the launch end at a preselected speed. The jet car is disengaged after the test speed is attained, and the dynamometer assembly and the carriage are allowed to coast at this speed into the test bed.

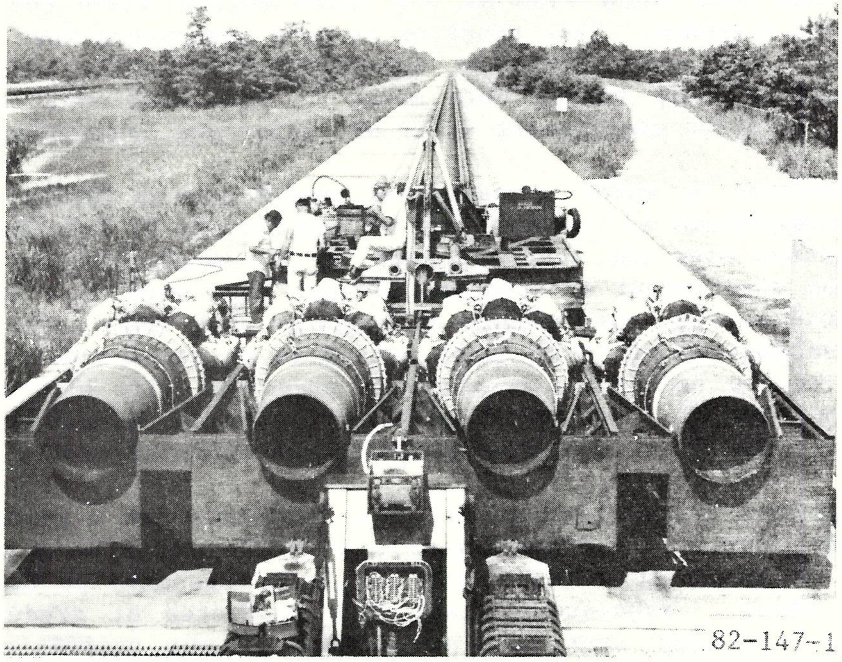

FIGURE 1. JET-POWERED PUSHER CAR FOR PROVIDING PRESELECTED SPEEDS TO TEST EQUIPMENT

The dynamometer and wheel assembly was designed and fabricated by the FAA and has the capability of simulating a jet transport tire-wheel assembly under touchdown and rollout conditions. The dynamometer is similar in design to one developed by NASA for the Langley Test Facility (reference 10). Figure 2 shows the dynamometer and wheel assembly and the details of the instrumentation for measuring vertical and horizontal loads at the axle. The assembly is pivoted about an axis contained in the dead-load carriage (carriage weighs 60,000 pounds). Figure 3 shows the hydraulic system for applying vertical load on the test tire. The hydraulic fluid in the system is forced into the cylinders by pressurized nitrogen. A similar hydraulic system is used for applying brakes to the test tire.

The dynamometer is instrumented to measure the vertical load on the tire, the horizontal force developed at the tire-runway interface, the angular velocity of the test tire, and the vertical motion of the dynamometer assembly relative to the dead-load carriage.

TEST SECTIONS.

The 300-foot test bed (figure 4) at the end of the track, was divided into seven 40-foot sections following a 20-foot section. The 20-foot section was intended for ensuring proper approach of the test wheel into the test section. The dimensional tolerance of the test surface was held within ±3/32 inch from horizontal level throughout the test bed.

Various surface treatments installed in the test bed are shown in figure 5. Section 2 which is not shown in the figure, contained reflex-percussive grooves having the same dimensions as those in the PCC surface that was tested earlier (reference 1). Section 1 contains a modified configuration of the reflex-percussive grooves: the dimensions are shown in figure 6. The purpose of this modification was to seek an optimized configuration for these grooves. The original grooves had a V-angle of 13° and a groove spacing of 4 1/2 inches. The new configuration has a 20° V-angle and the spacing is reduced to 3 inches. The flow area per unit length for the two configurations is approximately equal. This is the first modification to the reflex-percussive grooves originally developed by Klarcrete Limited, London, Canada; however, other modifications may be required to develop an optimized geometry. The grooves were installed by the machine shown in figure 7. It is anticipated that the modified groove configurations with even smaller spacing than 3 inches will not affect the overall cost of the reflex-percussive grooves because of the long life of the cutting heads and the high operating speed of the machine.

The saw-cut grooves were installed with the machine shown in figure 8. The square grooves of 1/4-inch size were spaced at 1 1/4 inches, 2 inches, and 3 inches between centers. Typical dimensions of the saw-cut grooves are shown in figure 6.

The plastic state grooving technique refers to grooving PCC while it is still in an uncured plastic state. Use of a ribbed vibrating float constructed on a bridge spanning the pavement width, and use of a roller with protrusions, or ribs, which form the grooves in the plastic concrete are two methods used in the United Kingdom and the United States (reference 6). Another method uses steel combs of various dimensions and tine spacing to form a groove-like texture in the plastic concrete pavement. The grooves are approximately 1/8 inch x 1/8 inch, spaced 1/2 inch center-to-center. The configuration provided in section 6 (figure 5) has the groove dimensions of the wire comb technique. The grooves were installed using a

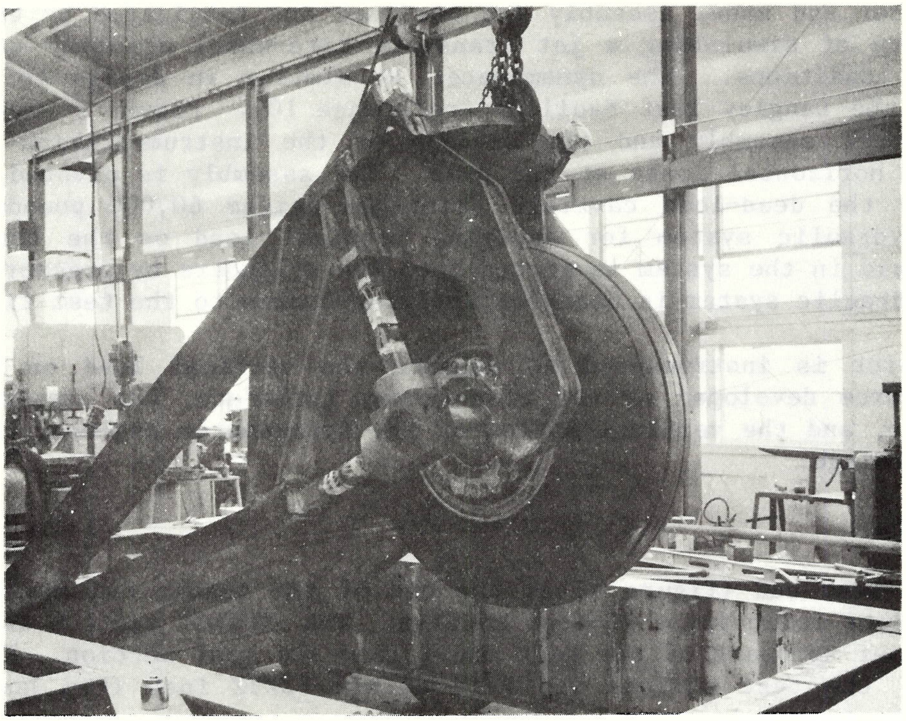

FIGURE 2. DYNAMOMETER AND WHEEL ASSEMBLY SHOWING VERTICAL AND HORIZONTAL LOAD LINKS

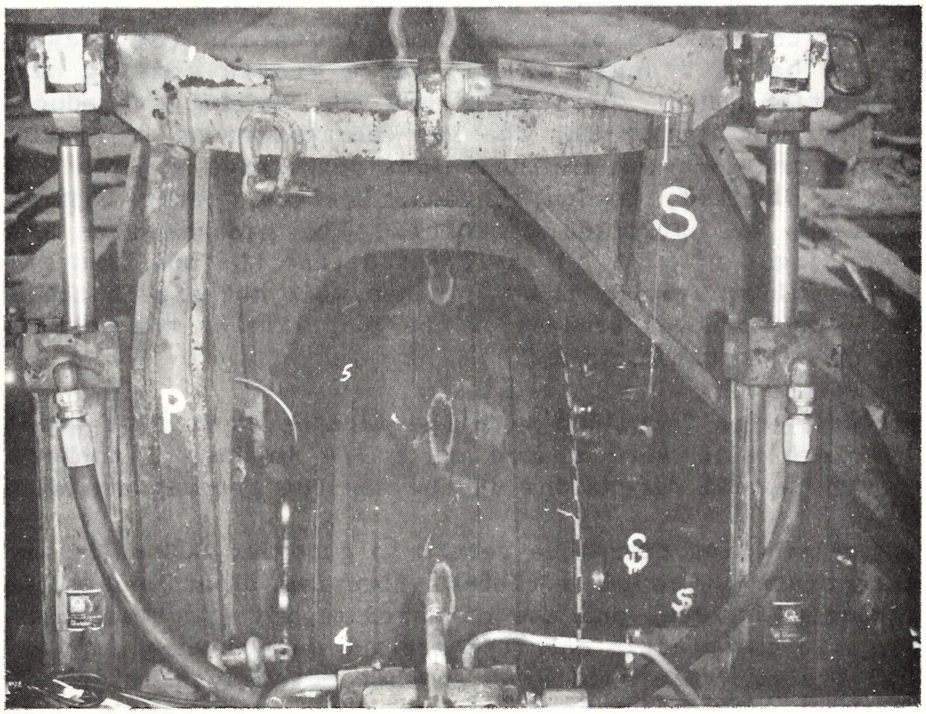

FIGURE 3. HYDRAULIC SYSTEM FOR APPLYING VERTICAL FORCES ON THE TIRE

diamond-tipped saw as for sections 3, 4, and 5. No technique has yet been devised to produce uniform grooving in the plastic state, and a wire-comb configuration cannot be installed in a plastic asphaltic concrete surface. However, the use of the diamond-tipped saw proved to be very satisfactory. It should be pointed out that this test program merely evaluates the braking performance and hydroplaning behavior of an aircraft tire on the plastic state configuration and not the technique of providing plastic state grooves.

The porous friction course was installed in section 7 (figure 5). Porous friction course is a thin asphaltic concrete overlay about 3/4-inch thick characterized by its open-graded matrix. It consisted of a 1/2-inch maximum size aggregate mix.

TEST PARAMETERS.

Four types of parameters were investigated in the test program: (1) tire, (2) pavement, (3) environmental, and (4) operational. The magnitude of each parameter was carefully selected to represent a value widely used or encountered by airlines or aircraft.

Among the various tire parameters, the important ones are: size, vertical load, inflation pressure, and tread design. All the test tires were 49 x 17, 26-ply rating, type VII. These tires are used on both the Boeing 727 and Boeing 747 aircraft and represent a large population of the tires used by the airline industry. To include the effects of tire tread design in terms of tread wear, two extremes were selected - a completely worn tire and a fully treaded tire (figure 9). Both tires were recapped except that the tread rubber was completely worn out on one. The tread wear was representative of the condition at which a tire would

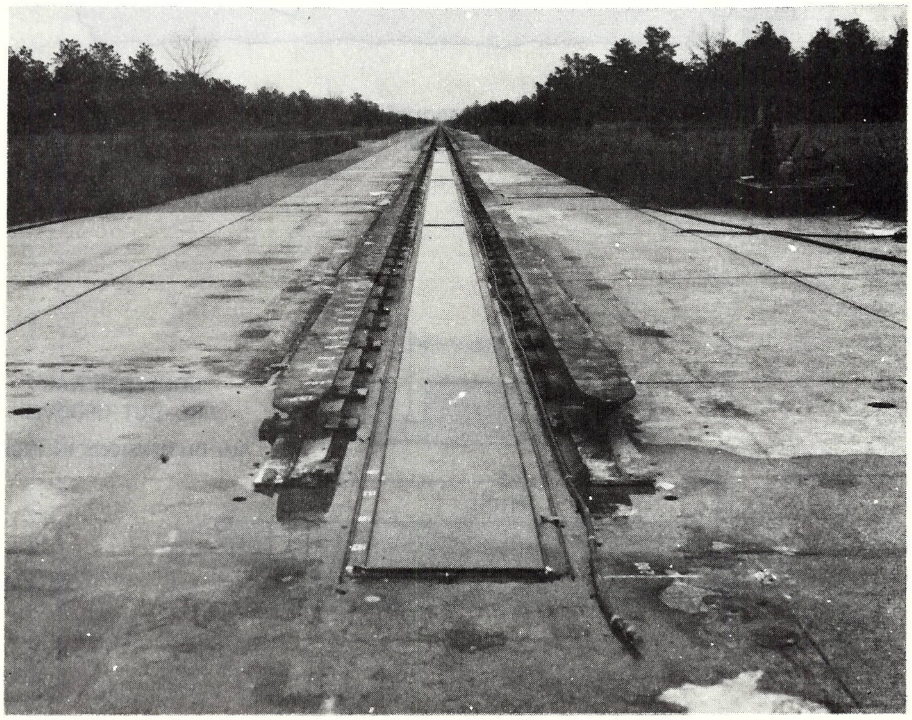

FIGURE 4. 300-FOOT TEST BED AT THE END OF THE TEST TRACK

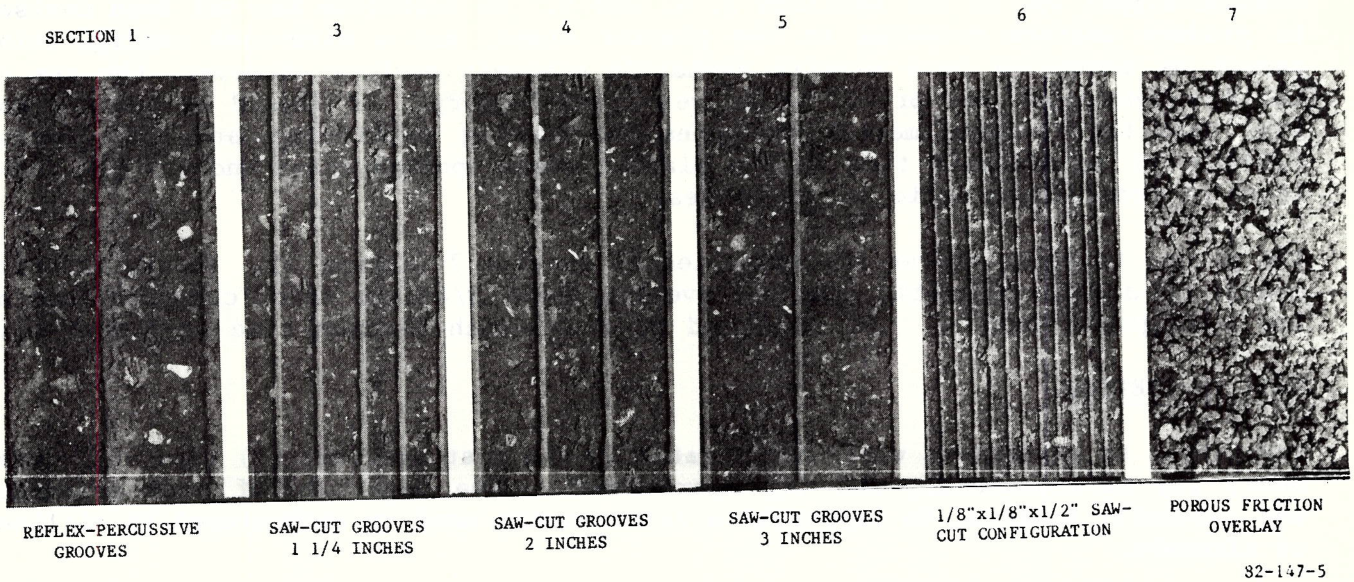

FIGURE 5. VARIOUS TEST SECTIONS OF THE 300-FOOT ASPHALTIC CONCRETE TEST BED (EACH SECTION IS 40 FEET LONG)

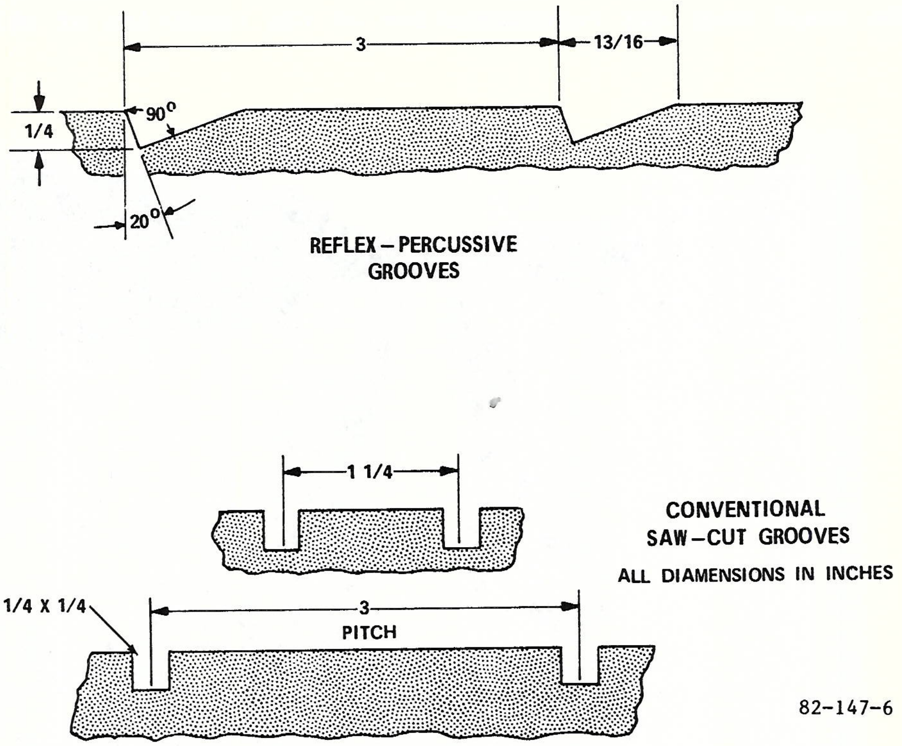

FIGURE 6. DIMENSIONS OF REFLEX-PERCUSSIVE GROOVES AND CONVENTIONAL SAW-CUT GROOVES

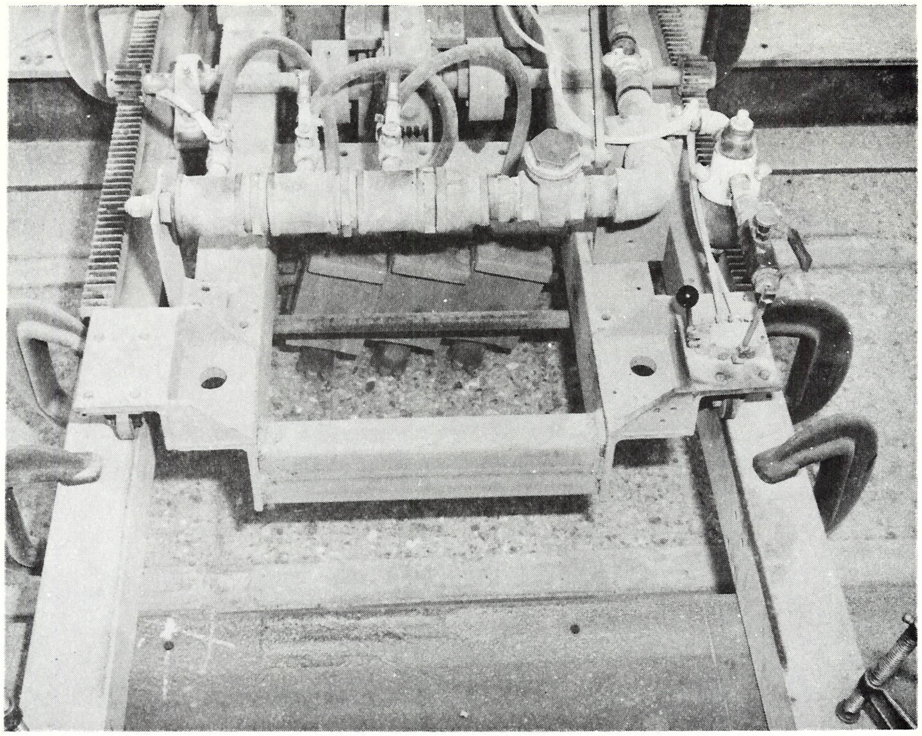

FIGURE 7. MACHINE FOR INSTALLING REFLEX-PERCUSSIVE GROOVES IN THE TEST SECTIONS

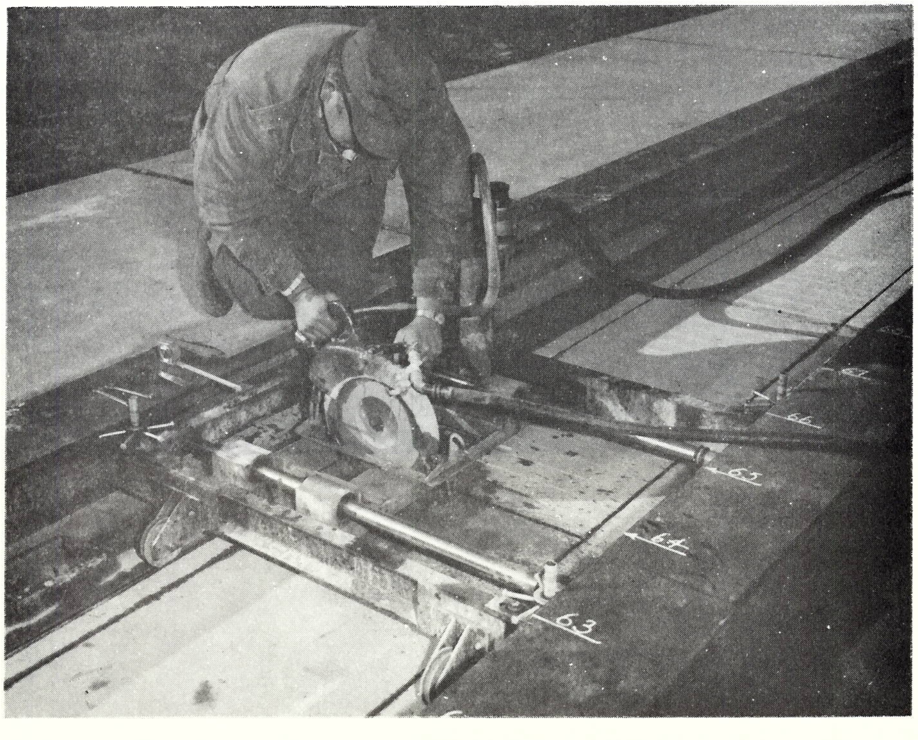

FIGURE 8. MACHINE FOR INSTALLING SAW-CUT GROOVES IN THE TEST SECTIONS

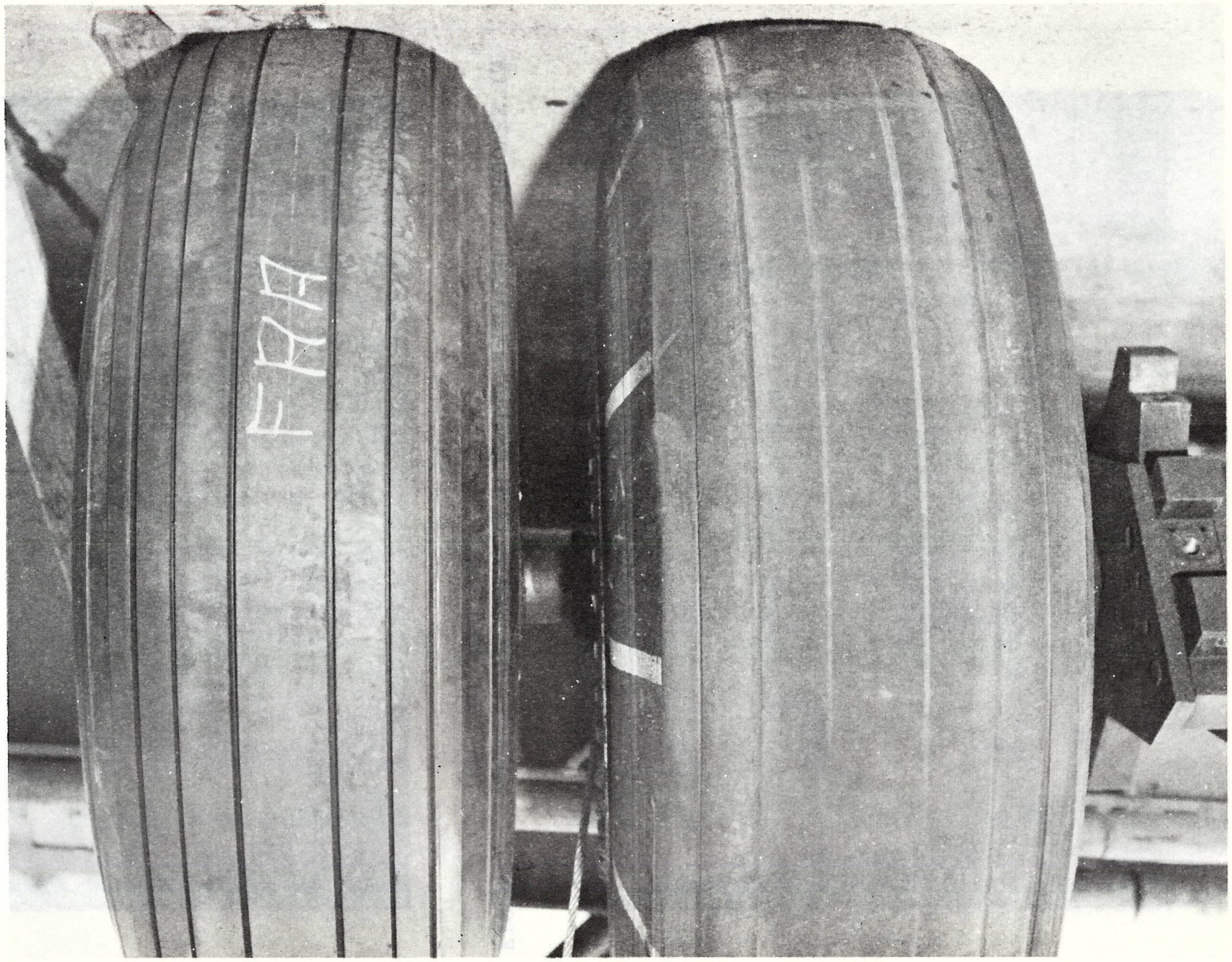

FIGURE 9. A NEW AND COMPLETELY WORN TIRE

normally be removed from the aircraft and be recapped. The total vertical load on the tire in these tests was 35,000 pounds - a value representing the average load on each landing wheel of a Boeing 727-200 aircraft. The tire inflation pressure was maintained at 140 pound/square inch, which represents the lower limit of the operational range of the Boeing 727 aircraft tires.

The pavement parameters included the type of surface, the type of surface treatment, and the groove spacings. Only one type of surface - the asphaltic concrete - was employed in this study. Testing on the PCC surface was completed in another study (reference 4).

The surface treatments included saw-cut grooves, reflex-percussive grooves, and porous friction course. Spacings for the saw-cut grooves were 1 1/4 inches, 2 inches, and 3 inches. An additional saw-cut groove configuration was tested which was representative of a configuration used when PCC is grooved in the plastic state. The nontreated (nongrooved) asphaltic concrete surface provided the baseline for performance comparison of all the surface treatments. The texture depth of the baseline surface was 0.014 inch.

Water depth was the only environmental parameter applied in the study for performance comparison. The water conditions on the test sections ranged from the "wet" to the "flooded." For the purpose of this study, a flooded condition indicates average water depth of 0.25 inch; average water depths of 0.10 ±0.01 inch are classified as puddled condition; and average water depths below 0.01 inch are referred to as the wet condition. The water depths for the flooded and puddled conditions were measured by the NASA water depth gauge.

The operational parameters included the test speed and the mode of wheel operation. The tests were run at speeds between 70 and 150 knots. The wheel was braked for all the tests but generally held in the rotating mode. Where wheel-lock occurred, the data were not used for comparing maximum braking performance.

The following is a summary of the test parameters investigated in this research:

Tire Parameters -
  Vertical Load : 35,000 pounds
  Inflation Pressure : 140 pounds/square inch
  Tread Design : Worn and treaded six groove
  Tire Size/Type : 49 x 17, 26 ply, type VII

Pavement Parameters -
  Type of Surface : Asphaltic concrete
  Microtexture : 0.014 Nongrooved Surface. Grease Smear Test
  Types of Surface Treatment : Saw-cut grooves, reflex-percussive V-grooves, porous friction overlay
  Groove Spacings : Saw-cut grooves
    1/4-inch square
      1 1/4-inch, 2-inch, 3-inch spacing
    1/8-inch square
      1/2-inch spacing
  Reflex-percussive V-grooves
    20° groove angle, 3-inch spacing

Environmental Parameters -
Average Water Depths : Less than 0.01 inch - wet
0.10 ± 0.01 inch - puddled
0.25 ± 0.01 inch - flooded

Operational Parameters -
Wheel Operation : Rolling to locked
Brake Pressure : 200 pounds/square inch - 2200 pounds/square inch
Speeds : 70 knots - 150 knots

TEST PROCEDURE.

A test tire was selected and mounted on the dynamometer assembly. The tire was not changed until completion of all the tests on that tire. Calibration of the instrumentation system was completed prior to the beginning of the test program. Calibration of the instrumentation for measuring horizontal forces in the tire-runway contact area was conducted by the use of a force plate. The loaded and braked tire was placed on the force plate which was supported on a set of frictionless rollers. Tangential load was applied on the plate by the use of a cable and pulley system. A transducer on the plate measured the applied tangential force which was later compared with the force measured by the dynamometer instrumentation system. The comparison shows a direct relationship between the two systems except for a zero shift of a small amount. The zero shift was constant for the applied load range between 1,000 pounds and 25,000 pounds, and was adjusted in the instrumentation system.

The dynamometer assembly, with mounted tire, was positioned at the launch end for the tests. A complete braking test consisted of the following steps:

1. Desired water depth was obtained on the test sections at the recovery end.

2. Jet engines were started at the launch end and set at the performance level to provide the preselected speed in the test section.

3. Jet car was released to propel the test equipment (dead load and dynamometer carriage). The test tire remained in a free-rolling state during this maneuver.

4. Jet car was braked and separated from the test equipment several hundred feet ahead of the test bed. This allowed the dead load and dynamometer to enter the first test section at the preselected speed. The test speed in the remaining sections were within 1 to 2 knots of the speed in the first section as computed from the analog traces.

5. Before the dynamometer assembly entered the first test section, the hydraulic systems were activated to apply the vertical load and brake pressure on the tire. (The magnitude of each was preselected.)

6. The wheel entered the test sections at preselected test conditions. The instrumentation was activated and the data were recorded.

7. As the wheel left the test bed, unloading and brake release were initiated and the test equipment was recovered by the use of arresting cables.

The above steps were accomplished by various personnel. Two persons were responsible for obtaining desired water depth in the test sections at the recovery end of the track. At the launch end, two persons were responsible for starting the engines and releasing the jet car. One more person was responsible for setting the engine performance level, the vertical load level, and the brake pressure level. At the recovery end, additional persons were responsible for the safe operation of the arresting cable system to recover and return the test equipment to the launch end for the next run.

DATA COLLECTION AND ANALYSIS.

The automatic data handling system is a multichannel analog recording system. It utilizes standard FM/FM telemetry for transmission of data from the mobile dead load. Both low- and high-level signals are frequency multiplexed for recording on a single magnetic tape. Recovery of these data in analog form permits an early validation and review of the dynamic data for further testing purposes.

Typical data collected in a test are shown in figure 10. The figure shows two traces each for horizontal force and vertical load on the tire. The coefficient of friction was computed from these four traces by dividing the horizontal force by the vertical load. Wheel revolutions were measured at two sensitivities to monitor wheel spin. The test speed was computed from the time/distance trace.

The results on the asphaltic concrete surfaces are shown in tables A-1 through A-3. The coefficients of friction in these tables represent the maximum available under each set of operating conditions; many more tests were conducted to obtain this maximum. A least-square fit was obtained between speed and coefficient of friction. A second order fit was found satisfactory because of a small scatter of data.

DISCUSSION

BRAKING PERFORMANCE.

The data showed a basic characteristic of friction-speed relationship — a drop in friction with increasing speed. Wet, puddled, and flooded water conditions were investigated.

Wet runway surfaces are normally encountered during or after a light or moderate rain. These surfaces may be saturated with water but would not have measurable water depth present on them. The puddled and flooded surfaces are representative of conditions that can be expected immediately after heavy rains of short and long durations, respectively.

On the wet nongrooved surface, a new tire performs better than a worn tire. While predominantly viscous pressures are developed in the entire contact area of a worn tire, a more complex mechanics takes place under a new tire; the viscous pressures under the tire groove is lower than under the rib. In addition, the water particles that try to escape (from the contact area of the worn tire) and cannot do so because of high tire side-wall pressures, find immediate relief in the circumferential grooves of the new tire. This results in a "drier" contact area and correspondingly a higher friction coefficient for the new tire (top solid line curve in figure 11).

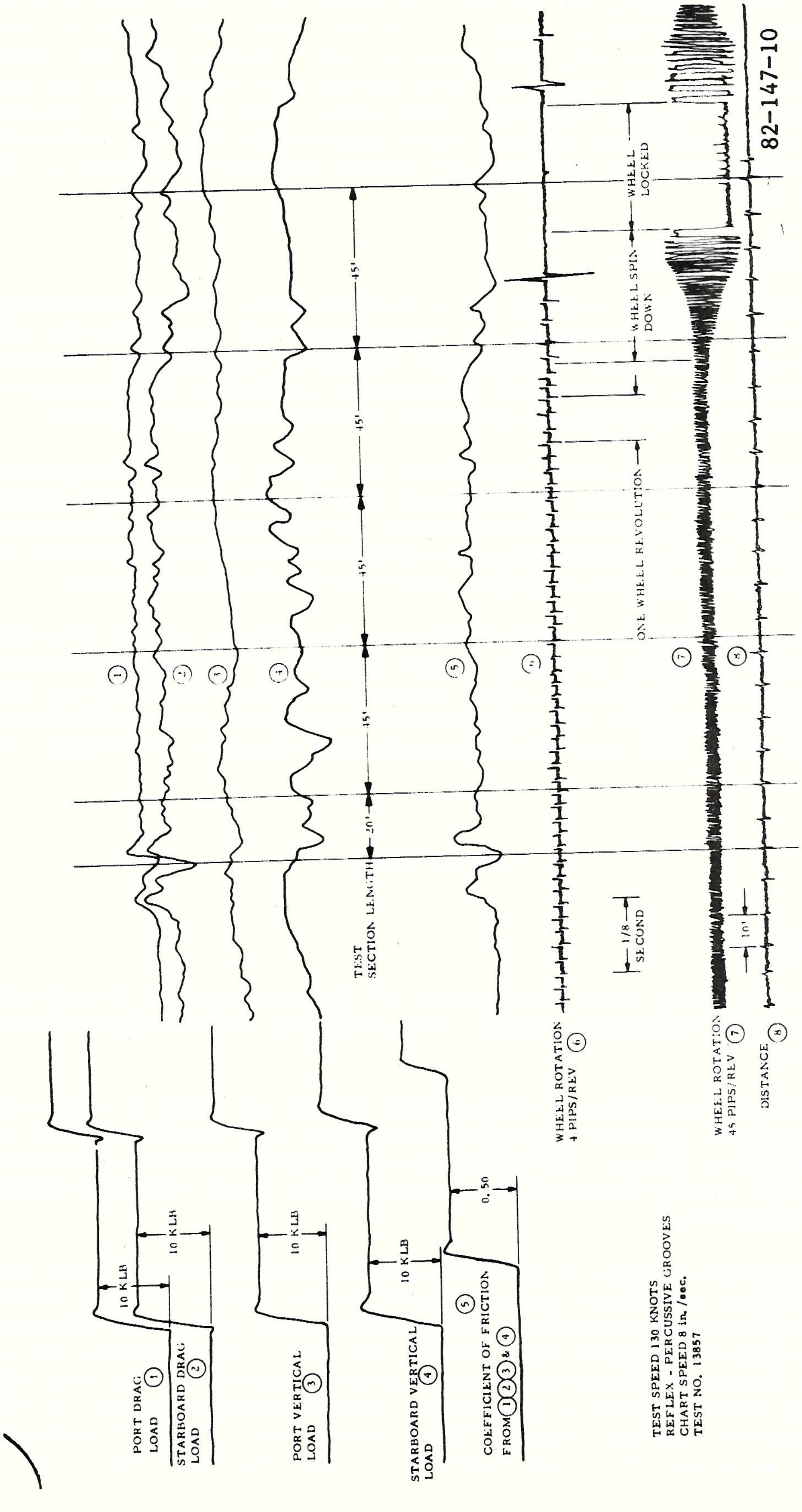

FIGURE 10. A TYPICAL DATA TRACE FOR A BRAKING TEST (FROM REFERENCE 4)

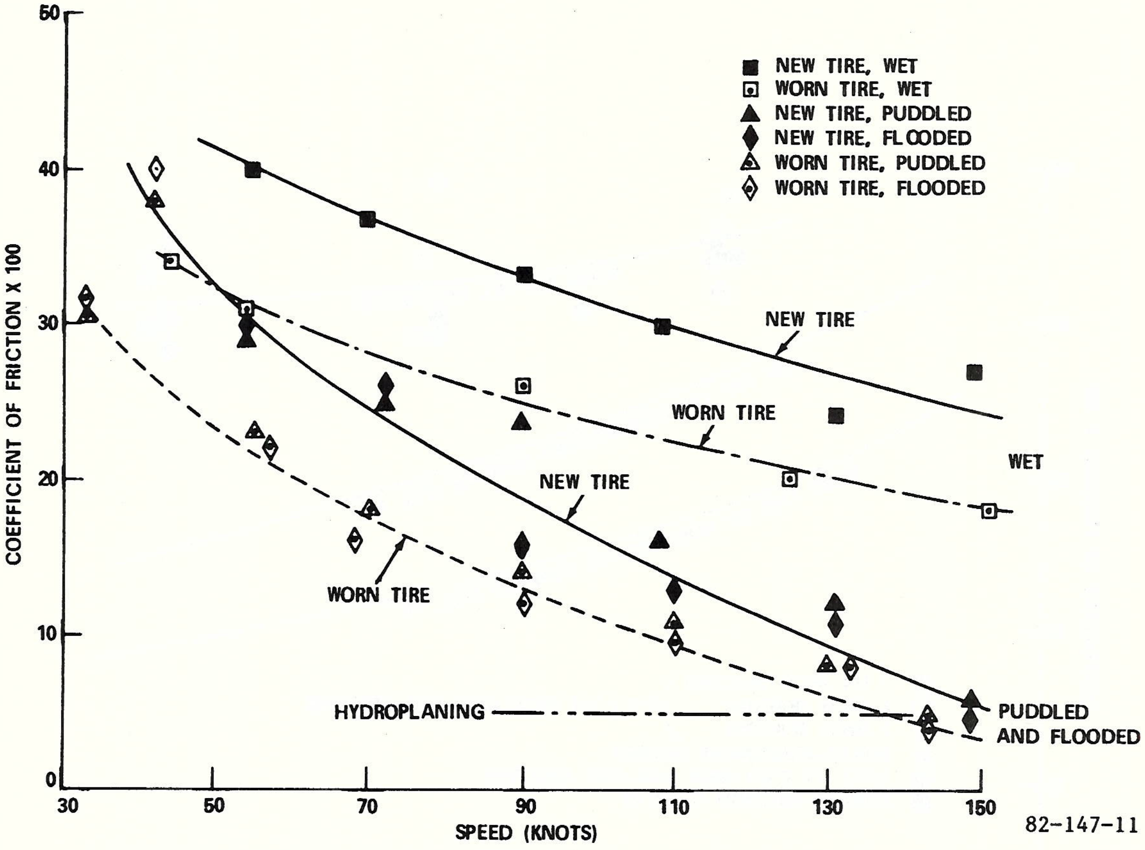

FIGURE 11. BRAKING TESTS ON NONGROOVED SURFACES WITH NEW AND WORN TIRES

The data for the puddled and flooded conditions on nongrooved surface are shown by the two bottom curves in figure 11; it can be seen that the braking performance is significantly lower than for the wet surface. The important aspect of this reduction in performance on puddled and flooded surfaces is the presence of hydrodynamic forces in the contact area, which along with the viscous forces have forced a partial separation of the tire from the runway surface. This effect is more pronounced at speeds in excess of 140 knots where conditions of imminent hydroplaning exist for both the new and worn tire.

When the wet runway surface is subjected to treatments included in this study, the braking performance of a worn tire is significantly better than on a nongrooved surface as shown in figure 12. Even the performance of the new tire on nongrooved surface is lower than that of the worn tire on treated surfaces. It should be pointed out that a single curve has been drawn for the performance of worn tires on all the treated surfaces. This choice is based on the fact that the available friction level for all the treated surfaces is high for the entire range of test speeds.

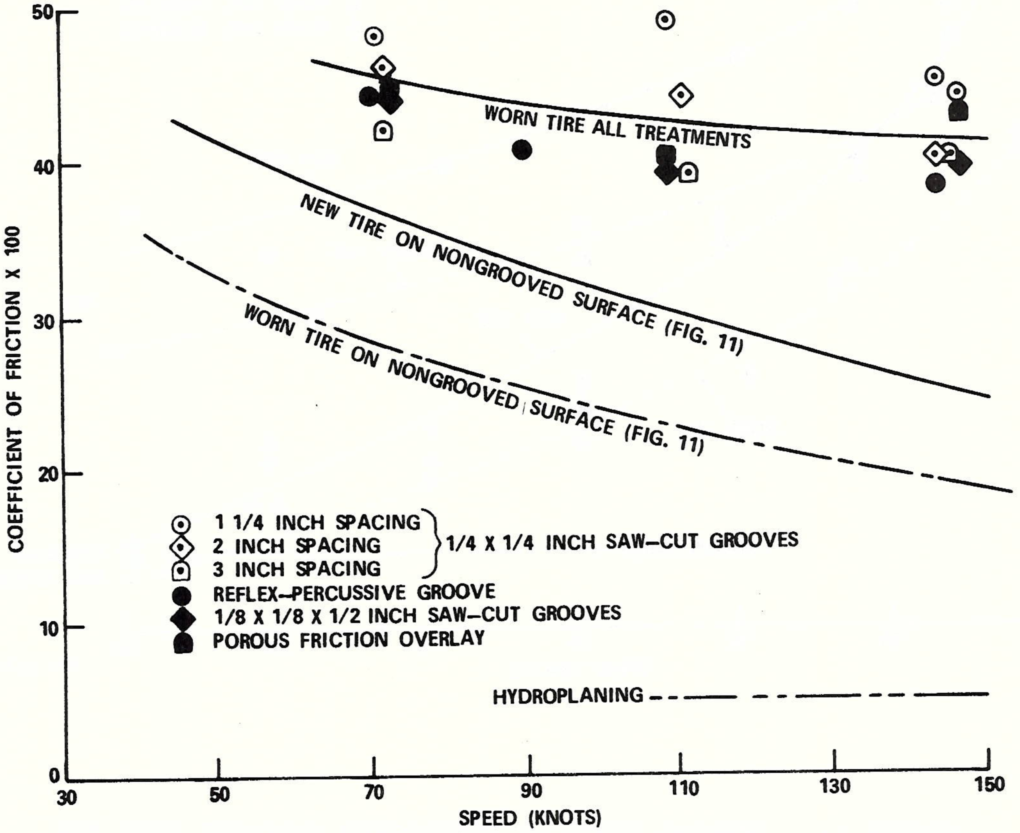

FIGURE 12. BRAKING PERFORMANCE OF A WORN TIRE ON WET SURFACE

An overall observation from figure 12 can be summarized as follows:

For operations of aircraft on predominantly wet runways, the introduction of tested surface treatments in the asphaltic concrete runway would provide sufficiently high friction coefficients that an aircraft equipped with worn tires will have excellent braking action throughout its landing and rollout maneuvers, and the available friction levels are insensitive to the type of surface treatment included in this study. Thus, the choice of the surface treatment to be applied to a runway can be based on both the cost and the benefits.

The braking performance of the worn tire on puddled surfaces with saw-cut grooves and reflex-percussive grooves is shown in figures 13 and 14. Figure 13 shows that for the 1/4-inch square grooves, the spacing has a distinct effect on the available friction level, for a given speed, the larger the spacing the smaller the value of available friction level. However, even with the largest groove spacing included in the test program (3 inches), the condition of hydroplaning is not reached within the speed range tested (70 to 150 knots).

The performance on the reflex-percussive grooves, and on 1/8-inch square saw-cut grooves is shown in figure 14. A single curve adequately represents the average performance of the two treatments. Figure 15 shows a composite of figures 13 and 14 to directly compare the braking performance on all the surfaces tested. The shaded area bounded by two light lines show the performance envelope on the saw-cut grooves. The dark line shows the performance on the reflex-percussive grooves and on the 1/8-inch square saw-cut grooves. In all cases, hydroplaning condition is not reached within the speed range employed in the test program. This figure indicates that the saw-cut grooves spaced 1 1/4 inches apart provide the highest levels of available friction on puddled surfaces with worn aircraft tire. The use of new tires will provide even higher levels of friction coefficients.

Figures 16 and 17 show the braking performance of a worn tire on flooded surfaces. In each case, a single curve shows the average performance on the surfaces tested. Figure 18 is a composite of figures 16 and 17 and clearly show that the performance on all the surfaces tested can be represented by a single curve; however, both curves are shown separately in this figure. In all cases, hydroplaning condition is not reached.

FRICTION COEFFICIENT AND STOPPING CAPABILITY.

The stopping distance of an aircraft can be determined from the available friction level when adjustments for aerodynamic drag and reverse engine thrust are made. A high friction coefficient is desirable for rapid deceleration of an aircraft. The introduction of grooves has been successful in providing an improvement in the available friction level over nongrooved surfaces. An interesting characteristic of the friction speed curve — its slope — in figures 11, 13, and 18 can provide additional information about the overall improvement the surface treatments have over nongrooved surfaces.

The slope of the friction-speed curve is continuously decreasing for all the surfaces — treated or nongrooved. However, although not enough data are available, figures 13 and 18 indicate that the slope is changing assymptotically beyond 140 knots and below 70 knots for treated surfaces. Thus, in a situation where a landing is attempted at a higher than normal speed, the wheel will not immediately experience friction levels corresponding to hydroplaning. Also, as the aircraft is being braked and going through successively lower speeds, it is encountering gradually increasing rate of change of friction level. This enables a shorter overall stopping distance. In comparison, the friction-speed curve for the nongrooved surfaces (figure 11) is uniformly decreasing near the high speed end and a state of hydroplaning will exist should the landing speed be higher than normal.

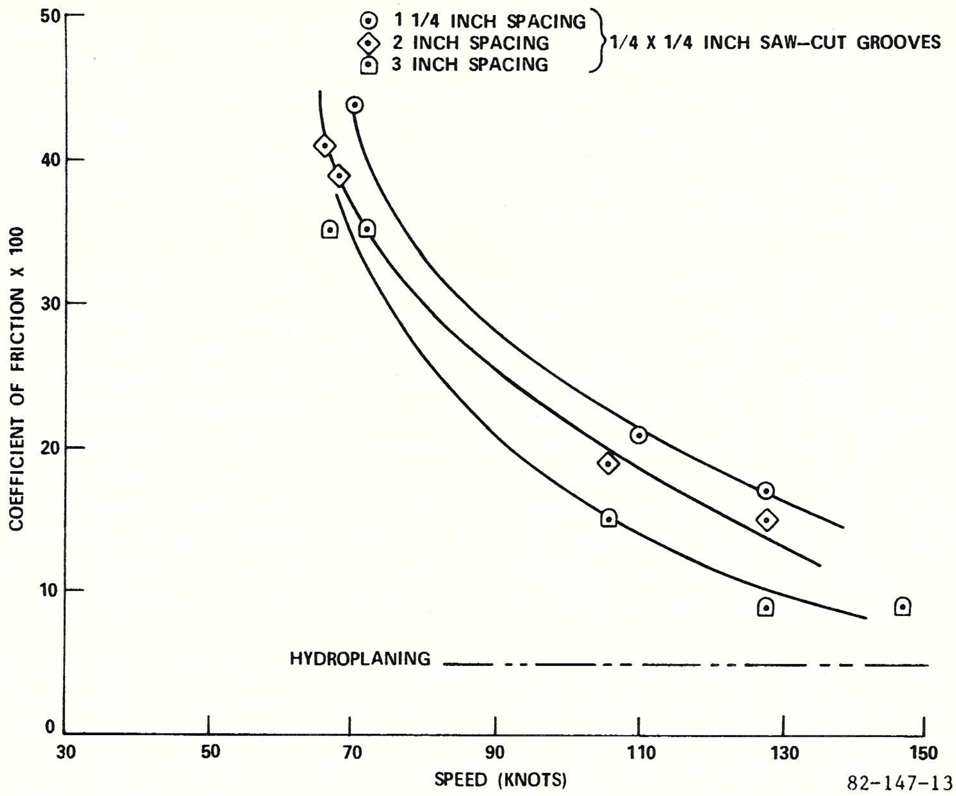

FIGURE 13. BRAKING PERFORMANCE OF A WORN TIRE ON PUDDLED SURFACE

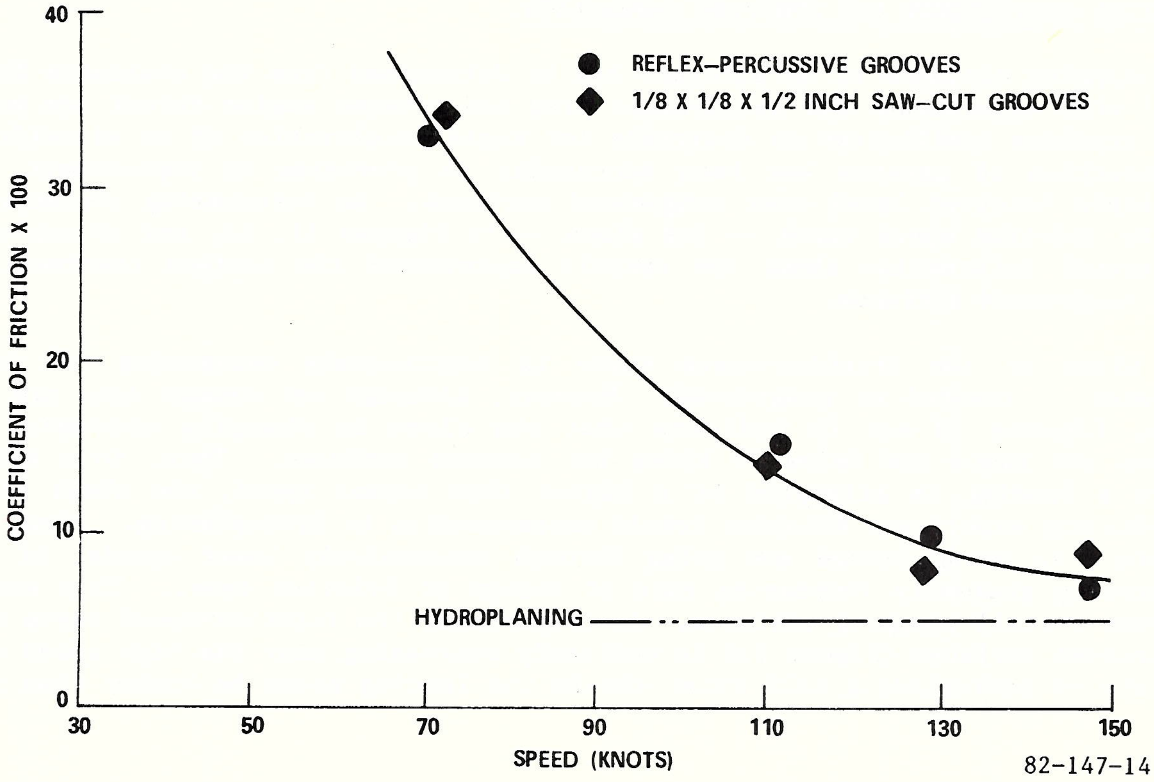

FIGURE 14. BRAKING PERFORMANCE OF A WORN TIRE ON PUDDLED SURFACE

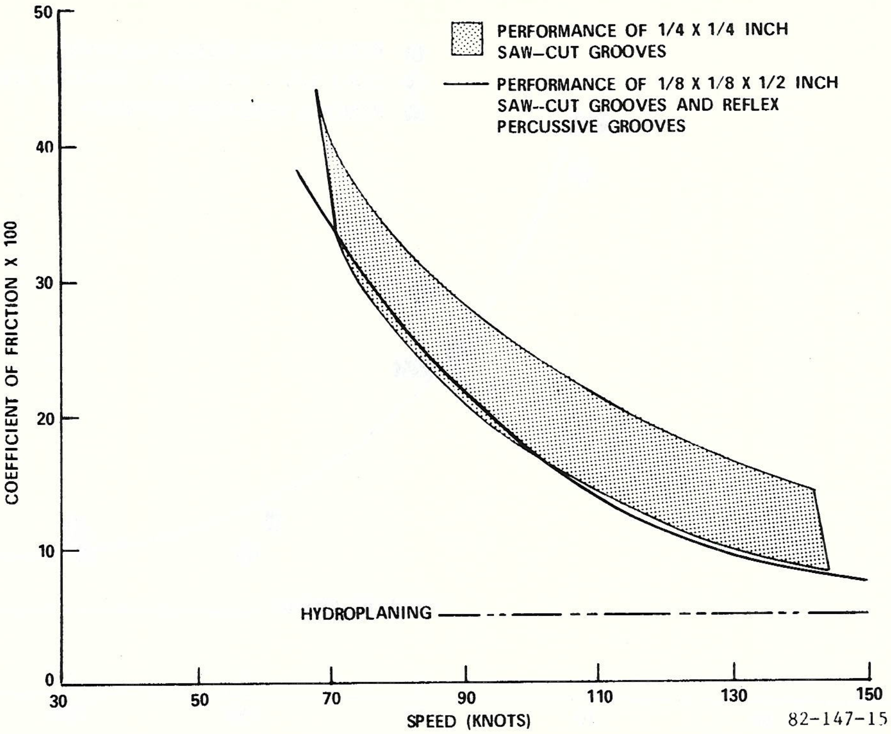

FIGURE 15. COMPARISON OF THE BRAKING PERFORMANCE UNDER PUDDLED CONDITION ON SAW-CUT AND REFLEX-PERCUSSIVE GROOVES

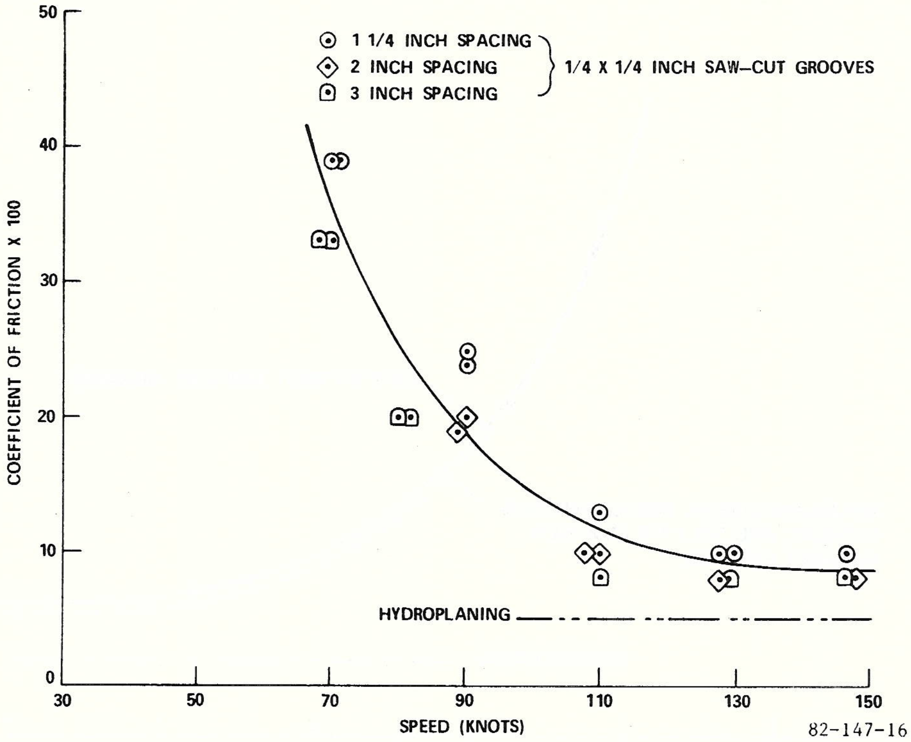

FIGURE 16. BRAKING PERFORMANCE OF A WORN TIRE ON FLOODED SURFACE

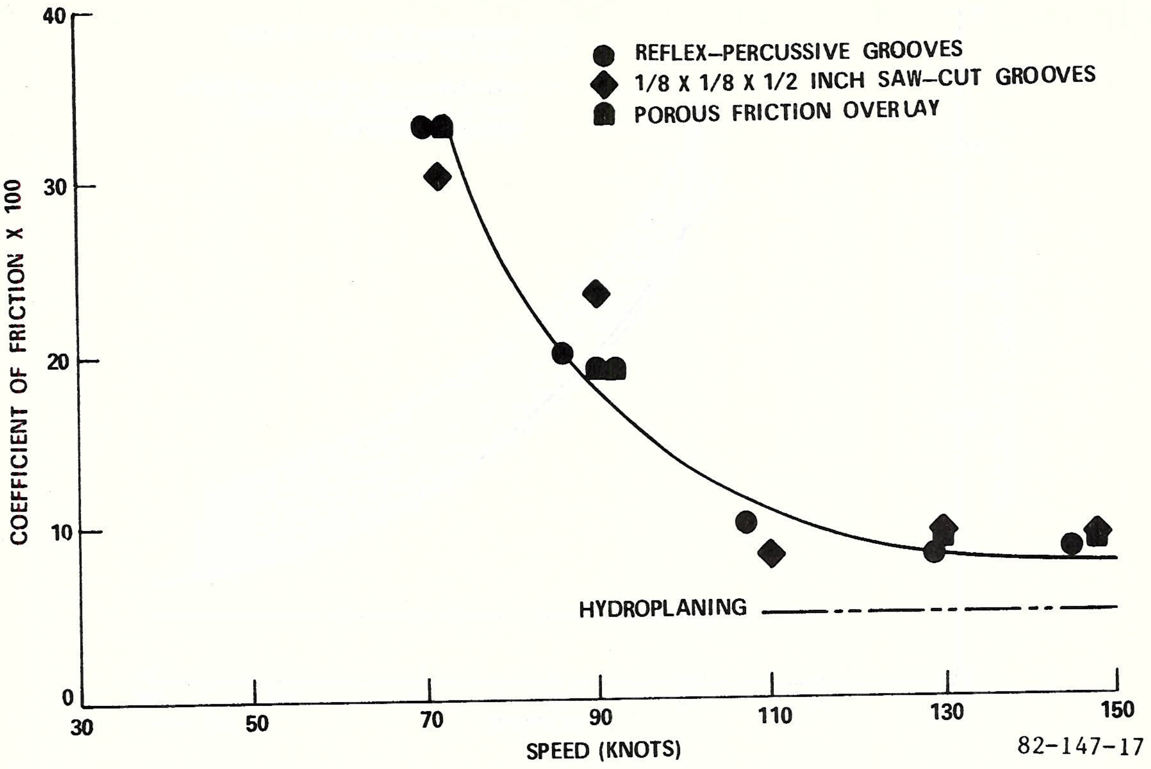

FIGURE 17. BRAKING PERFORMANCE OF A WORN TIRE ON FLOODED SURFACE

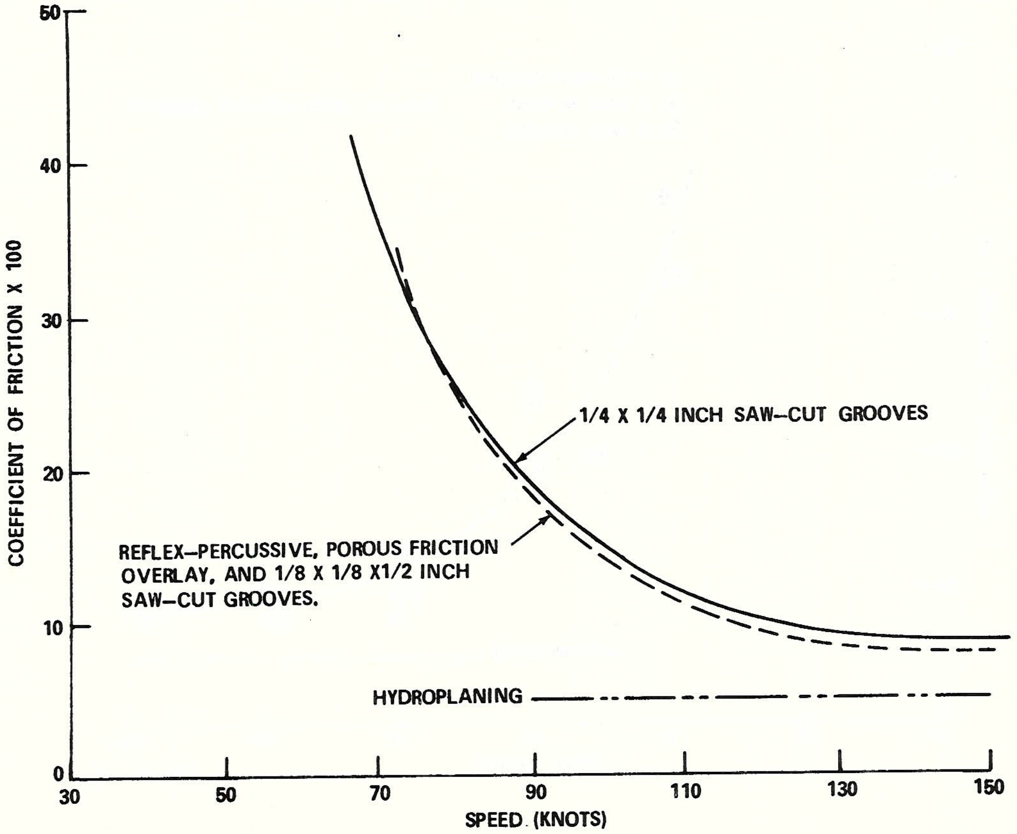

FIGURE 18. COMPARISON OF THE BRAKING PERFORMANCE UNDER FLOODED CONDITION ON ALL SURFACE TREATMENTS

FORCED WATER ESCAPE.

Water is forced out of the tire-runway interface when the tire travels on the runway; escape of water takes place in all directions. However, a large amount of water escapes from the rear and the sides of the contact area between the tire and the runway. Previous research has shown that during hydroplaning of a smooth tire on a smooth surface, the tire contacts the runway along the rear edge and the side edges of the contact area forming a horseshoe shape. The remaining area is separated by a film of water. The separation occurs, as pointed out earlier, as a result of the development of hydrodynamic and viscous pressures within the interface.

Although, this research did not include instrumentation to measure the water escape paths or amount of water escaped, an attempt is made here to explain how the grooves help water escape. When a worn tire travels over a wet (0.010 inch depth) surface having grooves, the pressures in the contact area are predominantly viscous. Because only a small amount of water is present in the contact area, all of it is expelled through grooves. Thus, all the surfaces provide high friction levels as shown by the solid-line curve in figure 19 (curve 1). The data scatter can be seen in figure 12. But, since the friction levels are high for the entire range of test speed, data scatter is irrelevant and all surface treatments included in this study will provide adequate safety in terms of stopping the aircraft quickly.

When the grooved surfaces are puddled, the hydrodynamic pressures become important. The additional water in the contact area must be removed to reduce the buildup of hydrodynamic pressures and to ensure high friction levels. When the grooves are spaced closer, water particles trying to escape through the rear of the contact area will find it easier to escape through the grooves and develop a "drier" contact area. However, a very large spacing will be completely ineffective in forcing the water out of the contact area because it will simulate a nongrooved surface and the friction forces will approach hydroplaning level as shown by curve No. 5 in figure 19. An optimum condition would be when all the water is expelled from the contact area in such a way that the water carrying capacity of the grooves is fully exhausted. This condition could be obtained by a certain combination of groove spacing and amount of water. Thus, for the same amount of wetness for which groove capacity of 3-inch spaced grooves is exhausted, the capacity of 1 1/4-inch spaced grooves will not and these grooves will provide a "drier" contact. The results on puddled surfaces with grooves verify this phenomenon: curve No. 2 shows these results. The shaded area bounded by two lines shows the extent of the forced water escape as a function of groove spacing: the top boundary represents the 1 1/4-inch groove spacing and the bottom boundary represents the grooves spaced at 3 inches.

The puddled condition in this study (water depth 0.10 ±0.01 inch), thus, represents a water condition where groove spacing is a factor in determining the maximum friction levels available. Clearly the grooves at 1 1/4-inch spacing provide better braking action. However, the spacing of 3 inches will provide sufficient braking to allow a gradual reduction in speed to develop further braking. It should be noted that hydroplaning is avoided for all spacings.

When the grooved surfaces are flooded, the reduced groove spacing does not improve the available friction levels. It can be seen from curve No. 3 (figure 19) that the available friction levels are slightly below the bottom of the shaded

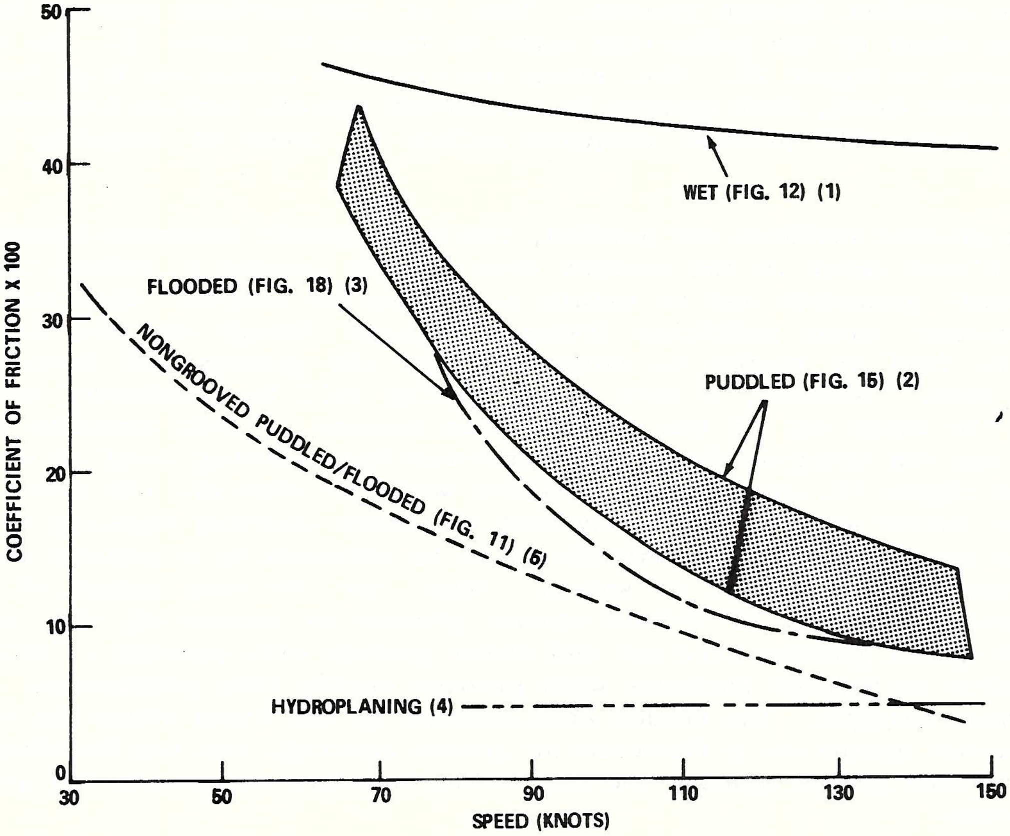

FIGURE 19. COMPARISON OF ALL SURFACE TREATMENTS UNDER WET, PUDDLED, AND FLOODED CONDITIONS

area for the puddled condition. Also, only a single curve represents the performance on all the treated surfaces. For the flooded surfaces, the grooves are filled with water even before the passage of tire over them. Then, the inertia of water particles retards the escape of water in all directions when the tire does travel over the grooves. The result is that the available friction levels are insensitive to the groove spacings.

SAW-CUT GROOVES, REFLEX-PERCUSSIVE GROOVES, AND POROUS FRICTION OVERLAY.

For the asphaltic concrete surface under "wet" and "flooded" conditions, the reflex-percussive grooves, the porous friction overlay, the 1/8 inch x 1/8 inch x 1/2 inch saw-cut grooves, and the 1/4-inch square saw-cut grooves of various spacings perform alike in terms of available friction levels when a full-scale aircraft tire is braked on these surfaces. However, the spacing of the 1/4-inch square saw-cut grooves influence the available friction levels on "puddled" surfaces: the smaller spacing provides higher friction levels. The reflex-percussive grooves, the 1/8 inch x 1/8 inch x 1/2 inch saw-cut grooves and the 3-inch spaced saw-cut grooves provide similar results on puddled surfaces.

Since a previous study (reference 4) has included the cost analysis of various grooving methods, it would only be necessary in this study to accept those results. However, a new cost analysis would be desirable to reflect new developments during the past several years. The previous study had shown that the saw-cut grooves spaced 3-inches apart in PCC could provide a cost savings of approximately 25 percent over the grooves spaced 1 1/4-inches apart. It also showed that the reflex-percussive grooves in PCC offer even higher cost savings: these grooves could cost as low as half the cost of saw-cut grooves at 1 1/4-inches spacing.

The reflex-percussive grooves need refinements to offer a cut as clean as in PCC. This may require a modified cutting head and a different impact frequency for the head. These changes may be necessary to compensate for the viscoelastic nature of asphaltic concrete surface. With the modifications, the reflex-percussive cutting process would be a viable cost competitive method to the saw-cut grooves. But, realistic cost estimates and full savings potential can only be affirmed after application of these grooves on an operating airport.

CONCLUSIONS

The following conclusions are drawn from the findings of this research. These conclusions are valid for asphaltic concrete surfaces and for the operating parameters included in the test program.

1. Where the seasonal and topographical conditions consistently produce "puddled" water conditions on the runways, the type of surface treatment has a significant influence on the braking performance of an aircraft tire. Although, all the surface treatments alleviate hydroplaning, the saw-cut grooves spaced 1 1/4 inches provide the maximum values of friction levels.

2. Where the seasonal and topographical conditions consistently produce either "wet" or "flooded" water conditions on the runways, the type of surface treatment has an insignificant effect on the braking performance of an aircraft tire on these runways. All the surface treatments alleviate hydroplaning.

3. The reflex-percussive grooves (spaced at 3 inches), the porous friction overlay, and the saw-cut grooves spaced at 3 inches perform comparably at all wetness conditions, and all alleviate hydroplaning.

4. If performance were the only criterion for the selection of a surface treatment, it is only at those airports where seasonal and topographical conditions produce "puddled" runway conditions that the choice of one treatment will be beneficial over another. However, if performance were not the only criterion, any surface treatment could be selected based on cost, since all the treatments provide sufficient braking to allow a gradual reduction in the speed of the aircraft and thus develop further braking.

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TABLE A-1. COEFFICIENT OF FRICTION - SPEED RELATION ON NONGROOVED SURFACE

	Worn Tire		New Tire	
	Speed (Knots)	μ x100	Speed (Knots)	μ x100
Wet:				
	44	34	54	40
	54	31	70	37
	90	26	90	33
	125	20	108	30
	151	18	131	24
			149	27
Puddled:				
	33	31	42	38
	55	23	54	29
	70	18	72	25
	90	14	90	24
	110	11	108	16
	130	8	131	12
	143	5	149	6
Flooded:				
	33	32	42	40
	57	22	54	30
	68	16	72	26
	90	12	90	16
	110	10	110	13
	133	8	131	11
	143	4	149	5

μ - Coefficient of Friction

TABLE A-2. COEFFICIENT OF FRICTION - SPEED RELATION ON GROOVED SURFACE

Worn Tire

	1 1/4-Inch Spacing		2-Inch Spacing		3-Inch Spacing	
	Speed (Knots)	μ x100	Speed (Knots)	μ x100	Speed (Knots)	μ x100
Wet:						
	71	48	72	46	72	42
	109	49	111	44	112	39
	144	45	144	40	146	40
	147	44				
Puddled:						
	70	44	66	41	67	35
	110	21	68	39	72	35
	128	17	106	19	106	15
			128	15	128	9
					147	10
Flooded:						
	71	39	70	39	68	33
	90	24	89	19	70	33
	90	25	90	20	85	20
	110	13	108	10	86	20
	128	10	110	10	110	8
	130	10	110	10	128	8
	147	10	128	8	147	8
			148	8		

μ - Coefficient of Friction

TABLE A-3. COEFFICIENT OF FRICTION - SPEED RELATION ON SURFACES WITH OTHER GROOVES AND TREATMENTS

Worn Tire

	Reflex-Percussive Grooves		Plastic-State Grooves		Porous-Friction Grooves	
	Speed (Knots)	μx100	Speed (Knots)	μx100	Speed (Knots)	μx100
Wet:						
	70	44	73	48	73	49
	90	41	109	39	109	40
	144	38	147	40	147	43
Puddled:						
	70	33	72	34		
	111	15	110	14		
	129	10	128	8	-	-
	147	9	147	9		
Flooded:						
	70	33	72	30	72	33, 33
	86	20	90	23	90	19
	107	10	110	8	91	19
	129	8	130	9	130	9
	145	9	148	9	148	9

μ - Coefficient of Friction